Field Crops Research 117 (2010) 219–225

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Row spacing, tillage system, and herbicide technology affects cotton plant growth and yield

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ARTICLE INFO

Article history:
Received 28 September 2009
Received in revised form 10 March 2010
Accepted 11 March 2010

Keywords:
Coastal Plain soil
Ultra-narrow row cotton

ABSTRACT

Cotton (*Gossypium hirsutum* L.) producers are faced with numerous production choices including cotton varieties, herbicide technology, tillage systems, and row spacing. A study was conducted to compare cotton production across conventional, glyphosate-tolerant, and glufosinate-tolerant varieties in both conventional and conservation tillage systems for standard row (102 cm) and narrow row (38 cm) cotton planting patterns. The experiment was conducted during the 2004–2006 growing seasons at the Field Crops Unit, E.V. Smith Research Center, near Shorter, AL in long-term tillage plots. Data collection included plant populations within row spacings, plant biomass and height at 1st square, mid-bloom, and lint yields. Plant biomass measured at 1st square and mid-bloom was affected by growing season with 38 cm cotton plant biomass averaging 34% greater in 2004 and 2005, however, the effect of tillage system was contradictory within the growing season. Mid-bloom plant biomass also varied across growing seasons with 21% more plant biomass recorded in 38 cm rows averaged across all three growing seasons. Plant heights were shorter for 38 cm cotton compared to 102 cm cotton, regardless of growth stage or tillage system. No differences in cotton development were observed across varieties. Cotton planted in 38 cm rows yielded equivalent to 102 cm cotton during two of the three experimental years and was superior to 102 cm cotton the remaining year, which corresponded to the best growing season observed during the experimental period. These results indicate that 38 cm cotton production can produce yields that are at least equivalent to standard 102 cm cotton, despite differences in plant development. The productivity of a narrow row cotton production system may be attractive to some growers, but economic evaluations are required to determine if the system is profitable on a large scale based on equivalent or marginal lint yield increases.

Published by Elsevier B.V.

1. Introduction

Throughout the United States, cotton is typically planted in rows > 76 cm (Vories et al., 2001; Williford, 1992); however, rising production costs, in conjunction with reduced crop prices, has prompted interest in narrow row cotton production and conservation tillage systems to improve productivity and optimize net returns (Gwathmey et al., 2008; Jost and Cothren, 2000; Nichols et al., 2003). Narrow row cotton has become synonymous with ultra-narrow row (UNR) cotton and is defined as cotton planted into rows that are ≤38 cm and harvested with a finger-type stripper (Nichols et al., 2003; Vories et al., 2001). Conservation tillage systems include some form of non-inversion tillage combined with high residue winter cover crops.

One barrier to the early adoption of UNR cotton was weed control, but the development of transgenic cultivars with an herbicide-resistant trait renewed interest in this production practice (Vories and Glover, 2006; Wilson et al., 2007). Herbicide-resistant varieties, particularly glyphosate-resistant (Roundup Ready®) varieties, have been overwhelmingly adopted since their release in 1997 (Dill, 2005; Gianessi, 2005). Consequently, large cotton areas were continuously treated with glyphosate, and in some areas the result has been the emergence and heavy selection pressure for glyphosate-resistant weeds. Recent glyphosate-resistant weed issues throughout the Southeast has led to the promotion of glufosinate-tolerant (Liberty Link®) cotton varieties that may serve as an alternative choice for growers with glyphosate-resistant weed problems.

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0378-4290/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fcr.2010.03.003

Plant populations typical for traditional cotton row spacings range from 7.4–14.8 plants/m^2 (Larson et al., 2007). Increased seeding rates for UNR cotton are required to decrease branching and assist harvest with a finger-type stripper and compensate for imprecise grain drills that are used to plant narrow cotton rows (Delaney et al., 2002; Larson et al., 2007). Individual plant production is decreased, but compensated by more plants/area. As a result of the renewed interest in UNR cotton due to herbicide-resistant technology, Delaney et al. (2002) reported recommended final plant populations ranging from 19.8–49.3 plants/m^2, while Nichols et al. (2003) reported values of 17.3–29.7 plants/m^2.

The use of herbicide-resistant cotton cultivars has added new costs of production; specifically associated technology fees for UNR cotton and the increased seeding rates. The technology fees account for a significant proportion of seed cotton production costs (Larson et al., 2007). High plant populations in UNR cotton production systems favor the use of a less expensive conventional cotton variety that does not have associated technology fees. A conventional cotton variety may be a viable alternative to herbicide-resistant cultivars in UNR cotton production. A decrease in row width results in rapid canopy development, speeding up canopy closure and potentially reducing weed competition (Marois et al., 2004). Complete canopy development may occur within 30 days for UNR cotton compared to 60–75 days for traditional row widths (Marois et al., 2004). Nichols et al. (2004) found that cotton yields in narrow rows were equivalent 2 out of 3 years between transgenic and conventional cotton varieties with a slight advantage observed for transgenic cultivars.

Another production system cotton growers may utilize to offset increased production costs and depressed crop prices is a conservation tillage system that includes high residue cover crops. Highly degraded soils may be improved physically, chemically, and biologically by utilizing conservation systems (Langdale et al., 1990; Reeves, 1997). The use of winter cover crops maintained on the soil surface maximize residue and protect the soil from erosion, particularly during winter months when precipitation exceeds evapotranspiration (Balkcom et al., 2007). Daniel et al. (1999) found that cover crop residue combined with no-till cotton production systems conserved more soil moisture compared to a conventional tillage system during low rainfall growing seasons. Coarse textured soils found across the Coastal Plain region of the Southeast are prone to soil compaction and previous research has documented that non-inversion tillage designed to maximize below ground disruption, while maintaining surface residue, benefits cotton yields (Raper et al., 2007; Reeves and Mullins, 1995; Touchton et al., 1986). High residue cover crops have also been shown to inhibit early season weed growth by limiting sunlight exposure and producing allelopathic chemicals, which suppresses weed seed germination prior to canopy closure (Barnes and Putnam, 1983; Reeves et al., 2005; Teasdale and Mohler, 2000).

These same marginal soils that have demonstrated cotton responses to conservation tillage systems may also benefit from a switch to UNR cotton. Benefits previously discussed related to conservation systems, such as moisture conservation, weed suppression, and decreased soil erosion have also been attributed to UNR cotton (Gwathmey and Hayes, 1996; Krieg, 1996; Marois et al., 2004; Nichols et al., 2004). Despite the potential advantages of combining UNR cotton with high residue conservation systems, information about the performance of UNR cotton production across different herbicide technologies and tillage systems is limited. Thus, our objective was to compare early and mid-season plant growth, early and mid-season plant heights, and cotton lint yields across three cotton varieties with different herbicide technologies (conventional, glyphosate-tolerant, and glufosinate-tolerant) planted in standard 102 cm rows and 38 cm row patterns for both conventional and conservation tillage systems.

2. Materials and methods

2.1. Site description

This experiment was initiated in the fall of 2003 at the E.V. Smith Research Center, Field Crops Unit near Shorter, AL (32° 25.763′N, 85° 53.117′W) on a Compass sandy loam (coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults). The experiment remained in the same location for 3 years with no re-randomization of treatments. The experimental area utilized for this study contained conventional tillage and conservation tillage plots that were originally established over 15 years ago. These plots allowed a comparison of treatments among mature tillage systems and eliminated any transition effects into conservation tillage.

The experimental design contained a split–split plot treatment restriction in a randomized complete block design with four replicates. The main plots consisted of row spacings (38 cm vs 102 cm row spacing), the subplots were varieties represented by three different herbicide technologies (conventional, glyphosate-tolerant, and glufosinate-tolerant), and the sub-subplots were tillage systems (conventional and conservation tillage). All conservation tillage plots will be referred to as no-tillage from this point forward. The varieties were selected from the same parent line to minimize genetic differences among varieties and restrict the major variety difference to the specified genetic trait (i.e. herbicide technology). The parent line chosen was from Fibermax (Bayer Crop Sciences, Research Triangle Park, NC) and included FM966® as the conventional variety, FM960 RR® as the glyphosate-tolerant variety, and FM966 LL® as the glufosinate-tolerant variety.

A rye (Secale cereale L.) cover crop was drilled across the experimental area each fall at 101 kg/ha. All plots were paratilled (complete disruption) immediately following the cover crop planting operation to eliminate any subsurface soil compaction with the exception of fall 2003. During the first year of the study, no deep tillage was performed in any of the plots, and only surface tillage associated with the conventional tillage plots was performed where appropriate. Surface tillage in the conventional tillage plots consisted of multiple spring disk operations and a field cultivator operation to level and firm the plots, prior to cotton planting. In the no-tillage plots, cotton was direct-seeded into rye residue.

In February, 22–34 kg N/ha, as NH_4NO_3, was applied to the cover crop. Biomass samples were collected from each plot approximately 3 weeks before the anticipated cotton planting date immediately preceding chemical termination. The average cover crop biomass production across the experimental site was 3940, 3430, and 5000 kg/ha for 2004, 2005, and 2006, respectively.

All plots received 47 kg N/ha as a starter in the form of NH_4NO_3, prior to planting. An additional 67 kg N/ha was side-dressed as urea-ammonium nitrate (UAN). All cotton varieties were Cruiser® treated and planted with an in-furrow application of Temik® (5.6 kg/ha) and Terraclor® (11 kg/ha). Plots were planted on May 25, 2004, May 17, 2005, and May 17, 2006, respectively. The 38 cm cotton was planted with a Great Plains® (Great Plains Mfg., Inc., Salina, KS) precision drill at 25.9 plants/m^2, while the 102 cm cotton was planted with a John Deere 1700 MaxEmerge Plus™ (Deere & Co., Moline, IL) air planter at 19.8 plants/m^2. Initial plant populations were measured approximately 4 weeks after planting. All emerged plants were counted in three 3-m long sections within each of the 102 cm wide cotton plots. In the 38 cm wide cotton plots, three areas that measured 2.0 m long and 1.5 m wide were used for the counts. These dimensions were selected to equalize the counted area at approximately 9 m^2/plot. Whole plant biomass samples were collected by clipping all aboveground plant material at the soil surface from a 1 m^2 area within each plot at 1st square and mid-bloom. At the time of biomass collection, plant heights were measured from each plot by measuring 10 randomly selected plants from the soil surface to the terminal bud. These sample times averaged to approximately 48 and 74 days after planting, respectively across all 3 years.

Based on cooperative extension recommendations in the region, Prowl® (1.67 L/ha) was applied PRE to all conventional tillage plots and conventional varieties immediately following planting. Two POST applications of either Roundup Weathermax® (1.67 L/ha) or Ignite® (2.33 L/ha) followed by a split Staple® (0.09 L/ha) application was applied to corresponding herbicide-tolerant and conventional varieties at the 2- and 4-leaf growth stages. A final application (LAYBY) of Envoke® (0.01 L/ha) or Staple® (0.09 L/ha), depending on the year, was applied over the top to all 38 cm cotton, while a LAYBY application of Caparol® (2.33 L/ha) and MSMA® (3.11 L/ha) was applied as a PDS on the same day to the 102 cm cotton.

Each year, all cotton in the experiment was defoliated with Def 6® (1.17 L/ha), Prep (1.75 L/ha), and Dropp® (0.09 kg/ha). Cotton from two 2-m^2 sections within each plot was hand-harvested on October 4, 2004, October 11, 2005, and October 11, 2006, respectively. A subsample of seed cotton from each plot was ginned in a 20-saw tabletop micro-gin to determine ginning percentage. Lint yields were determined by weighing lint and seed collected from each plot and multiplying corresponding seed cotton by the ginning percentage of each plot.

2.2. Statistical analysis

All response variables were analyzed based on a general linear mixed model procedure using SAS software (Littell et al., 2006) (release 9.1, SAS Institute Inc., Cary, NC). Data were analyzed with rep, year, variety, spacing, tillage, and the interactions among year, variety, spacing, and tillage as fixed effects in the model, while replication × variety and replication × variety × spacing were considered random. The population variable was analyzed within each row spacing with rep, year, variety, tillage, and the interactions among year, variety, and tillage as fixed effects in the model, while replication and replication × variety × spacing were considered random. Covariance between years was modeled as a repeated measure. Least significant difference (LSD) mean comparison tests were used to distinguish differences between treatment means and were considered significant if $P \leq 0.05$. Compound symmetry or first order autoregressive was used to model covariance between years for each of the response variables. For some response variables, the error between years was not homogenous and heterogeneous compound symmetry covariance structure was used. Akaike information criteria was used to determine which covariance structure was best (Littell et al., 2006).

3. Results and discussion

3.1. Climate data

Rainfall and calculated heat units for the 2004, 2005, and 2006 growing seasons are shown in Table 1. Rainfall received during the 2004 and 2005 growing seasons was similar and averaged 49% higher than rainfall received during the 2006 growing season. Although, rainfall was greatest for the 2004 growing season, much of the rain can be attributed to an unusually wet June and a hurricane event in September (Table 1). Rainfall recorded during the 2005 growing season was steady throughout the year, but high rainfall amounts were recorded during July, a critical development period for cotton in the Southeast. Accumulated heat units averaged 16% greater during the 2005 and 2006 growing seasons compared to the 2004 growing season. The driest and warmest growing season was in 2006 (Table 1).

Table 1
Measured rainfall and heat units during the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Month	2004		2005		2006	
	Rainfall (mm)	Heat units[a]	Rainfall (mm)	Heat units	Rainfall (mm)	Heat units
May	12	130	15	174	0	227
June	178	525	39	502	18	563
July	62	638	215	656	93	715
August	99	557	87	646	99	712
September	147	430	37	547	103	426
October	0	48	45	141	2	110
Total	498	2328	438	2666	315	2753

[a] Heat units were calculated with the following formula $[(T_{max} + T_{min}/2) - 15.5\,^\circ C]$, where T_{max} = daily maximum temperature and T_{min} = daily minimum temperature. Calculations began on the day of planting and ended on the day of harvest.

3.2. Plant populations

Stand establishment in no-tillage cropping systems has always been a concern, particularly for narrow row cotton production that typically requires some type of grain drill for planting (Bauer et al., 2003). The difference in planter units required for plant establishment between row spacings in our study resulted in initial seeding rates that were 35% higher for 38 cm cotton compared to the standard seeding rate for 102 cm cotton. Since two different planters were used for two different systems, the population counts were confounded with planter units. As a result, no comparisons were made between 38 and 102 cm rows, but the plant population data was analyzed within row spacings (Table 2). Measured final plant populations from the glyphosate-tolerant variety were lower than those from the glufosinate-tolerant variety, but no different from the conventional variety in 38 cm cotton (Table 3). There was an interaction between tillage system and years for the 38 cm cotton. Measured final plant populations from the conventional tillage system were 22% lower than those observed for the no-tillage system in 2005 (Table 3). However, the opposite occurred in 2006 with conventional cotton populations 14% greater than no-tillage cotton (Table 3). A tillage system × year interaction was also observed for 102 cm cotton (Table 2), but the only difference between tillage systems within a year was in 2005. Measured final plant stands were 26% lower for conventional tillage cotton compared to no-tillage cotton (Table 3). A variety × year interaction was also observed in the 102 cm cotton (Table 2). The major difference occurred in 2006 with measured plant populations greatest from the glufosinate-tolerant variety (Table 3). The major differences observed for plant populations within row spacings appear to be related to environmental conditions due to the multiple interactions that include year. Research has indicated that final lint yields are relatively stable across a wide range of

Table 2
Analysis of variance *F*-values and *P*-values for cotton plant populations within 38 and 102 cm row spacings across the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Source of variation	Numerator df	38 cm rows		102 cm rows	
		F-value	Prob > *F*	*F*-value	Prob > *F*
Year (*Y*)	2	1.4	0.2596	**11.4**	**0.0001**
Variety (*V*)	2	**4.1**	**0.0368**	**11.0**	**0.0012**
Year × variety	4	1.1	0.3630	**3.5**	**0.0163**
Tillage (*T*)	1	0.5	0.4843	**24.8**	**0.0002**
Year × tillage	2	**13.5**	**≤0.0000**	**7.7**	**0.0017**
Variety × tillage	2	0.02	0.9761	3.2	0.0708
$Y \times V \times T$	4	1.0	0.4464	1.4	0.2382

The bold values were highlighted to indicate that the main effect or interaction was significant equal to or less than 0.05 as stated in the M and M section.

Table 3
Plant populations measured within row spacings across years, cultivars, and tillage systems during the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Variety (plants/m^2)							
38 cm cotton				102 cm cotton			
CV[a]	LL[a]	RR[a]	$LSD_{0.05}$[b]	CV	LL	RR	$LSD_{0.05}$[b]
15.4	16.5	15.1	1.2	13.0	14.3	13.2	0.6

Year	Tillage system (plants/m^2)					
	CT	NT	$LSD_{0.05}$[b]	CT	NT	$LSD_{0.05}$[b]
2004	15.5	14.6		13.2	13.5	
2005	13.9	17.8	1.7	11.2	14.1	1.0
2006	17.1	15.0		14.2	14.7	
$LSD_{0.05}$[c]	1.8		1.1			

Year	Variety (plants/m^2)			
	CV	LL	RR	$LSD_{0.05}$[b]
2004	12.2	14.0	13.7	
2005	12.7	12.9	12.4	1.2
2006	14.1	15.9	13.3	
$LSD_{0.05}$[c]		1.3		

[a] CT = conventional; LL = glufosinate-tolerant (Liberty Link®); RR = glyphostate-tolerant (Roundup Ready®).
[b] Compare any two means across varieties or tillage within year.
[c] Compare any two means across varieties or tillage within or across year.

population densities, however, the optimum population density does depend on environment (Bednarz et al., 2000). Boquet (2005) reported reduced boll number/plant and reduced boll weights combined with compensatory growth across an increasing plant density resulted in no change in lint yields across different plant densities. Bauer et al. (2003) suggested that seeding rates for UNR cotton ($\leq$25 cm) should be increased 20–25% with conservation tillage on Coastal Plain soils. Although not widespread, there are 38 cm air planters available, which may enable lower seeding rates to be used, due to more precise seed placement, but another planter would be another significant expense for the grower. However, benefits, such as increased light interception, weed suppression, and a possible decrease in soil water evaporation associated with rapid canopy closure should be considered (Burmester, 1996; Krieg, 1996; Snipes, 1996).

3.3. 1st square plant data

Three interactions were also observed for early season plant biomass measured at 1st square (Table 4). A year × spacing interaction (Pr > $F \leq 0.0001$) indicated that 38 cm cotton produced more biomass at 1st square the first two growing seasons, however no difference was observed the last year (Table 5). The 38 cm cotton produced 51% and 17% more biomass at 1st square compared to 102 cm cotton during 2004 and 2005, respectively. All other comparisons between row spacings were also significant across years (Table 5). However, the increase in plant biomass at 1st square does not appear related to plant height. Cotton plants at 1st square were taller for the 102 cm rows in 2004, 2005, and 2006 (Table 6) indicating that the difference in plant biomass was related to an increase in the number of plants per unit area for 38 cm rows. Other studies indicate plant height decreases as the row spacing is narrowed, but these measurements were collected at plant maturity and not observed or reported earlier in the season (Clawson et al., 2006; Jost and Cothren, 2000).

A year × tillage interaction for plant biomass (Pr > $F \leq 0.0001$) and plant heights (Pr > $F \leq 0.0001$) at 1st square showed conflicting results that depended on the growing season (Table 4). In 2004,

Table 4
Analysis of variance F-values and P-values for cotton dry weights and plant heights at 1st square across the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Source of variation	Numerator df	1st square dry weight		1st square plant height	
		F-value	Prob > F	F-value	Prob > F
Rep	3	1.2	0.3366	3.1	0.1897
Year	2	**257.5**	**≤0.0001**	**480.3**	**≤0.0001**
Spacing (S)	1	**22.4**	**0.0002**	**32.9**	**0.0105**
Year × S	2	**12.3**	**≤0.0001**	**10.6**	**0.0001**
Variety (V)	2	0.9	0.4100	0.6	0.5707
Year × V	4	1.7	0.1539	2.4	0.0618
V × S	2	0.6	0.5758	0.8	0.4624
Year × V × S	4	1.0	0.4012	1.3	0.2629
Tillage (T)	1	3.1	0.0899	**4.6**	**0.0449**
Year × T	2	**14.0**	**≤0.0001**	**21.6**	**≤0.0001**
S × T	1	**5.5**	**0.0273**	4.2	**0.0543**
Year × S × T	2	0.6	0.5329	0.2	0.8440
V × T	2	0.7	0.5242	0.3	0.7437
Year × V × T	4	1.9	0.1229	1.3	0.2815
V × S × T	2	0.2	0.7958	0.4	0.7039
Year × V × S × T	4	1.2	0.3379	1.5	0.2057

The bold values were highlighted to indicate that the main effect or interaction was significant equal to or less than 0.05 as stated in the M and M section.

plant biomass measured at 1st square was 23% lower from no-tillage plots, but this difference may be attributed to the lack of deep tillage the first year (Table 5). However, in 2005, the best growing season of the experiment, plant biomass was 16% greater in the no-tillage plots. Despite moisture conserving benefits of the conservation system, early season plant biomass was 32% greater in the conventional plots compared to no-tillage during the very dry growing season of 2006 (Table 5). Plant heights measured at 1st square across years and tillage systems followed the same trend as plant biomass at 1st square, except for 2006 (Table 6). Plant heights in 2006 were also much shorter compared to the other growing seasons.

A spacing × tillage interaction (Pr > F = 0.0273; Table 4) indicated that 38 cm cotton produced 28% more 1st square plant biomass than 102 cm cotton averaged across tillage systems (Table 5). The

Table 5
Cotton plant dry weights measured at 1st square during the 2004–2006 growing seasons across row spacings and tillage systems at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Year	Spacing (kg/ha)		$LSD_{0.05}$[a]
	38 cm	102 cm	
2004	1600	1057	174
2005	1770	1512	208
2006	599	534	136
$LSD_{0.05}$[b]	161		

Year	Tillage (kg/ha)		$LSD_{0.05}$[a]
	Conventional	No-tillage	
2004	1505	1152	162
2005	1520	1762	197
2006	645	488	115
$LSD_{0.05}$[b]	177		

Tillage system	Spacing (kg/ha)		$LSD_{0.05}$[c]
	38 cm	102 cm	
Conventional	1318	1130	148
No-tillage	1328	939	
$LSD_{0.05}$[b]	162		

[a] Compare means across spacing or tillage within year.
[b] Compare any two means across spacing, tillage, or variety across year.
[c] Compare spacing means within a tillage system.

Table 6
Cotton plant heights measured at 1st square during the 2004–2006 growing seasons across row spacings and tillage systems at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Year	Spacing (cm)		$LSD_{0.05}$[a]
	38 cm	102 cm	
2004	40.8	47.7	3.9
2005	44.1	55.4	
2006	24.2	28.3	
$LSD_{0.05}$[b]	3.9		
Year	**Tillage (cm)**		**$LSD_{0.05}$[a]**
	Conventional	No-tillage	
2004	45.7	42.8	2.4
2005	46.1	53.5	
2006	25.9	26.6	
$LSD_{0.05}$[b]	2.4		
Tillage system	**Spacing (cm)**		**$LSD_{0.05}$[c]**
	38 cm	102 cm	
Conventional	34.7	43.8	3.9
No-tillage	38.1	43.8	
$LSD_{0.05}$[d]	2.4		

[a] Compare any two means across spacing or tillage within year.
[b] Compare any two means across spacing or tillage within or across years.
[c] Compare any two means across spacing within tillage system.
[d] Compare any two means across spacing within or across tillage systems.

Table 7
Analysis of variance *F*-values and *P*-values for cotton dry weights and plant heights at mid-bloom across the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Source of variation	Numerator df	Mid-bloom dry weight		Mid-bloom plant height	
		F-value	Prob > *F*	*F*-value	Prob > *F*
Rep	3	1.0	0.4035	**10.7**	**≤0.0001**
Year	2	**443.6**	**≤0.0001**	**1138.1**	**≤0.0001**
Spacing (*S*)	1	**19.9**	**0.0005**	**68.1**	**≤0.0001**
Year × *S*	2	1.4	0.2440	2.4	0.1003
Variety (*V*)	2	0.9	0.4125	1.5	0.2310
Year × *V*	4	0.6	0.6906	1.9	0.1193
V × *S*	2	1.0	0.3744	1.5	0.2404
Year × *V* × *S*	4	1.4	0.2414	0.4	0.8371
Tillage (*T*)	1	**17.0**	**0.0006**	**5.4**	**0.0268**
Year × *T*	2	0.6	0.5382	**3.4**	**0.0425**
S × *T*	1	0.7	0.4013	2.8	0.1063
Year × *S* × *T*	2	1.2	0.3086	0.5	0.5855
V × *T*	2	1.1	0.3409	0.6	0.5795
Year × *V* × *T*	4	0.3	0.8859	0.1	0.9794
V × *S* × *T*	2	2.2	0.1344	0.7	0.5192
Year × *V* × *S* × *T*	4	0.8	0.5342	1.1	0.3574

The bold values were highlighted to indicate that the main effect or interaction was significant equal to or less than 0.05 as stated in the M and M section.

102 cm conventional tillage cotton also produced 20% greater 1st square plant biomass than 102 cm no-tillage cotton. This difference may be attributed to the number of emerged plants, because no difference in plant heights was observed at 1st square between tillage systems planted in 102 cm rows (Table 6). The weaker spacing × tillage interaction ($Pr > F = 0.0543$; Table 4) observed for 1st square plant heights shows that the 38 cm cotton was shorter early in the season compared to 102 cm cotton, however, no-tillage cotton planted in 38 cm rows was taller than conventional tillage cotton in 38 cm rows (Table 6).

3.4. Mid-bloom plant data

Plant biomass measured at mid-bloom was significant for years, row spacing and tillage systems (Table 7). The greatest mid-bloom plant biomass was measured during the 2005 growing season followed by the 2004 growing season, while the lowest mid-bloom plant biomass was recorded in the very dry 2006 growing season (Table 8). Mid-bloom plant biomass in 2006 was 55% and 78% lower than the 2004 and 2005 growing season, respectively. The 102 cm cotton produced 21% less plant biomass at mid-bloom compared to 38 cm cotton, while no-tillage plots produced 14% less plant biomass at mid-bloom when averaged over varieties, row spacings, and all 3 years of the experiment (Table 8). The difference in plant heights between row spacings was also present at mid-bloom ($Pr > F \leq 0.0001$; Table 7) with 102 cm cotton 15% taller than 38 cm cotton (Table 9). Similar to 1st square measurements, the increased number of plants/area for 38 cm cotton at mid-bloom influenced plant size more than plant heights. Mepiquat chloride, a plant growth regulator designed to control cotton growth (Nichols et al., 2003), was only applied one time to all plots in the experiment. This application occurred in 2005, which corresponded to when the largest plants were recorded. Observed differences were not confounded by plant growth regulator applications. The year × tillage interaction ($Pr > F = 0.0425$; Table 7) observed for plant heights measured at mid-bloom indicate differences in height were observed between tillage systems only in 2005 and 2006 (Table 9). Cotton plant heights averaged 4 and 13% taller for the no-tillage system in 2005 and 2006, respectively.

3.5. Lint yields

Lint yields were strongly influenced by year as indicated by three interactions that included year. Although a year × spacing interaction ($Pr > F = 0.0194$; Table 10) was observed, 38 cm lint yields were equivalent to 102 cm lint yields within all three growing seasons (Table 11). In 2005, superior lint yields were produced compared to the other two growing seasons (Table 11), which can be attributed to the favorable growing conditions (Table 1). Despite wind damage from a hurricane, 2004 lint yields were greater across both row spacings compared to 2006 lint yields (Table 11) produced under dry conditions (Table 1). Jost and Cothren (2000) compared 38 and 102 cm cotton row spacings along with 19 and 76 cm row spacings 2 years in Texas. One year was very wet and no yield differences were observed among row spacings. The other year was drier and hotter, and the narrow row spacings (≤38 cm) performed better than the wider row spacings (≥76 cm). The observed yield increase during the dry year was attributed to earlier boll set prior to moisture limiting conditions (19 cm rows), and more bolls per unit area with a higher plant population (38 cm rows) (Jost and Cothren,

Table 8
Mid-bloom plant biomass measured across years, row spacings, and tillage systems during the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Variable	Crop year (kg/ha)			Row spacing (kg/ha)		Tillage system[a] (kg/ha)	
	2004	2005	2006	38 cm	102 cm	CT	NT
Mid-bloom plant biomass	3995	8101	1803	5078	4187	4937	4329
$LSD_{0.05}$		428		425		311	

[a] CT = Conventional tillage; NT = no-tillage.

Table 9
Cotton plant heights measured at mid-bloom during the 2004–2006 growing seasons across row spacings and tillage systems at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Spacing (cm)			$LSD_{0.05}$[a]
38 cm		102 cm	
66.5		76.4	2.5
Year	Tillage (cm)		$LSD_{0.05}$[b]
	Conventional	No-tillage	
2004	71.4	70.7	4.7
2005	95.1	98.5	4.3
2006	43.6	49.2	1.9
$LSD_{0.05}$[c]	4.4		

[a] Compare means across spacing.
[b] Compare means across tillage within a year.
[c] Compare any two means across tillage or years.

2000). No yield advantage was observed in our study for narrow row cotton during the dry 2006 crop year, but the inclusion of a conservation tillage system may have influenced lint yields more than row spacing.

A year × tillage interaction ($Pr > F = 0.0001$; Table 10) was also observed, but the response to tillage was inconsistent. Conventional tillage cotton yields were 21% greater compared to no-tillage cotton during the 2004 growing season (Table 11). However, this yield increase could be attributed to the lack of deep tillage during the first year of the experiment. Typically, Coastal Plain soils require some form of deep tillage to eliminate subsurface soil compaction, which will enhance root growth and subsequent nutrient and water uptake (Busscher et al., 1988; Schwab et al., 2002). In 2005, no yield differences were observed between tillage systems (Table 10), but favorable growing conditions were prevalent throughout this crop year (Table 1). However, the dry, hot growing conditions of 2006 favored the no-till system, which produced yields 10% greater than the conventional tillage system (Table 11). The observed advantage in early season growth for conventional tillage (Table 5) did not correspond to an increase in lint yields (Table 11). The larger plants measured at mid-bloom in 102 cm cotton and conventional tillage cotton (Tables 8 and 9) also produced no consistent yield increases. Bauer et al. (2003) also reported an inconsistent response to tillage for UNR cotton (<25 cm). No-tillage yields between 2004 and 2006

Table 10
Analysis of variance *F*-values and *P*-values for cotton lint yields across the 2004–2006 growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Source of variation	Numerator df	Lint yield	
		F-value	Prob > *F*
Rep	3	1.1	0.4042
Year	2	**237.7**	$\leq$**0.0001**
Spacing (*S*)	1	0.2	0.6966
Year × *S*	2	**4.3**	**0.0194**
Variety (*V*)	2	**6.6**	**0.0057**
Year × *V*	4	**4.3**	**0.0040**
V × *S*	2	0.6	0.5648
Year × *V* × *S*	4	0.9	0.4807
Tillage (*T*)	1	1.2	0.2951
Year × *T*	2	**11.2**	**0.0001**
S × *T*	1	0.6	0.4343
Year × *S* × *T*	2	0.6	0.5465
V × *T*	2	0.4	0.6723
Year × *V* × *T*	4	0.6	0.6533
V × *S* × *T*	2	0.1	0.9207
Year × *V* × *S* × *T*	4	0.2	0.9476

The bold values were highlighted to indicate that the main effect or interaction was significant equal to or less than 0.05 as stated in the M and M section.

Table 11
Lint yields measured during the 2004–2006 growing seasons across row spacing, tillage systems, and cotton varieties at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL.

Year	Spacing (kg/ha)			$LSD_{0.05}$[a]
	38 cm	102 cm		
2004	972	1055		90
2005	1604	1480		128
2006	810	818		86
$LSD_{0.05}$[b]	100			
Year	Tillage (kg/ha)			$LSD_{0.05}$[a]
	Conventional	No-tillage		
2004	1110	917		94
2005	1536	1547		130
2006	774	855		77
$LSD_{0.05}$[b]	111			
Year	Variety (kg/ha)			$LSD_{0.05}$[a]
	Conventional	Glufosinate-tolerant	Glyphosate-tolerant	
2004	1025	1002	1014	111
2005	1598	1423	1605	156
2006	750	734	959	105
$LSD_{0.05}$[b]		133		

[a] Compare means across spacing, tillage, or variety within year.
[b] Compare any two means across spacing, tillage, or variety across year.

were statistically similar, despite no deep tillage and hurricane damage in 2004 compared to unfavorable growing conditions of 2006 (Table 11). The benefits associated with conservation systems under unfavorable growing conditions seem apparent when 2006 conventional yields are compared to no-tillage yields across any year (Table 11).

A year × variety interaction ($Pr > F = 0.0040$; Table 10) also indicated that 2005 produced the best overall yields, but the conventional and glyphosate-tolerant variety produced higher yields compared to the glufosinate-tolerant variety (Table 11). In 2005, conventional cotton produced 12% greater yields, while glyphosate-tolerant cotton produced 13% greater yields compared to glufosinate-tolerant cotton. However, glyphosate-tolerant cotton yields were greater than both conventional and glufosinate-tolerant cotton yields by 29% in 2006. No lint yield differences were observed between cotton varieties in 2004, but 2006 glyphosate-tolerant cotton yields were equivalent to all variety yields in 2004. All other comparisons across years and varieties were significantly different (Table 11). Results from Georgia indicate that glufosinate-tolerant varieties have not been adopted by growers on a wide-scale due to poor agronomic performance (UGA, 2007). In contrast, other results have shown yield increases for glufosinate-tolerant cotton compared to glyphosate-tolerant cotton, but this was attributed to heavy weed pressure in glyphosate-tolerant cotton that contained glyphosate-resistant Palmer amaranth, highlighting a management option available to growers with glyphosate-resistant weed problems (Culpepper et al., 2009). Our results indicate that when yield potential was high, the glufosinate-tolerant variety did not perform as well, validating grower concerns with this herbicide technology in cotton production, regardless of row spacing.

4. Conclusions

The effects of row spacing, cotton variety, and tillage system were examined across three growing seasons at the Field Crops Unit of the E.V. Smith Research Center near Shorter, AL. The variables examined included plant populations within row spacings, plant biomass and plant heights at 1st square and mid-bloom, and lint yields. The growing season, as well as tillage, also influenced plant biomass at 1st square. Greater plant biomass was recorded early in the season for 38 cm cotton, but this can be attributed to higher plant populations, since 38 cm cotton was shorter than 102 cm cotton. Mid-bloom plant biomass varied across growing seasons, and more plant biomass was recorded in 38 cm rows averaged across all three growing seasons. The conventional tillage system produced more biomass than the no-tillage system, but increased lint yields did not correspond to the increase in plant biomass. Our treatment effects on lint yield were influenced by growing season as interactions occurred between year and spacing, year and tillage, and year and variety. Cotton planted in 38 cm rows yielded equivalent to 102 cm cotton during two of the three experimental years and superior the other year. Although 38 cm cotton production could fit into some cotton grower's operations, the equivalent or marginal increase for lint yields observed in our study requires further economic evaluation to determine whether the additional investment in equipment and additional seed costs make this system profitable.

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